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The Evolution of the Spectrum of a Star during its Growth from a Nebula.

By W. E. WILSON, D.Sc., F.R.S.

(Received June 5,—Read June 8, 1905.)

In considering the probable evolution of the spectrum of a star in its different stages from a nebula,* let us first consider a mass of gas at a sufficiently high temperature to be able to radiate waves of light into the surrounding space. If this mass of gas were sufficiently rare to be transparent to all wave-lengths of light except those which it is itself able to radiate, its spectrum would be a bright-line one.†

Sir William Huggins was the first to show, in 1864, that many nebulae gave a simple spectrum of a few bright lines. These lines show the presence of hydrogen and helium. Some other faint lines are also seen, but their origin is at present not known.

As our supposed mass of gas, spherical for simplicity, slowly cools, its density must increase at the centre, and as the density became sufficiently great for the gas to become nearly opaque for light of all wave-lengths, the bright lines of the spectrum, which at first were thin and faint, would continually thicken and finally become a continuous spectrum. When the nucleus had become dense enough to be quite opaque, if no scattering of the light coming from the deepest parts of the nucleus is in operation, the mass would radiate as freely as a “black body,” and the spectrum would be an absolutely continuous one. The late Professor G. F. FitzGerald suggested

* [Note, June 8, 1905.—On sending this paper to Professor Larmor for reading at the Royal Society, my attention was again directed by him to the very complete discussion of some of the subjects treated in it that is contained in Sir W. and Lady Huggins’ ‘Atlas of Representative Spectra,’ published by Wesley and Son, 1899. I am glad to be able to refer to this high authority in support of the views herein expressed. Thus it is concluded there that hydrogen, and especially helium, are not confined to any one class of stars, but are common to all stars and nebulae. The influence of partial pressure of the gas, of convection currents, of pressure due to increasing force of gravity, of increase of temperature as well as fall, are also traced, with a general conclusion (p. 75) that “principal types of star spectra should not be interpreted as produced by great original differences of chemical constitution, but rather as successive stages of an evolutionary progress bringing about such altered conditions of density, temperature, and mingling of the stellar gases as are sufficient presumably to account for the spectral differences observed.” See also British Association Presidential Address, 1891.]

† Schuster, ‘Astro-physical Journal,’ January, 1905.

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in 1896* that in such a mass of heated gas there would be powerful convection currents, and that these would be able to scatter, and deflect back into the interior, rays coming from the lower depths of the gaseous mass, so that such a mass of heated gas, however thick, could never reach the stage of radiating as a "black body." In fact it would emit the same spectrum as the mass gave before it was dense enough to be quite opaque. If the nebula consisted originally of an enormous mass of extremely attenuated hydrogen, and mixed with it minute proportions of the vapours of other elements such as iron, magnesium, etc., the spectrum of these other elements would not become visible until, in the lapse of time, the elements of high atomic weight gradually gravitated to the centre of the mass, so as to arrive at a density great enough to give rise to the emission of their bright-line spectra. In this gradual process of concentration of the heavier elements to the centre, they would displace the hydrogen, helium, and other elements which have small atomic weight. The heavier elements would in time become the source, in the nucleus of the nebula, of the bright, banded, and almost continuous spectrum; while the lighter and now cooler elements like hydrogen and carbon would begin to give a dark-line spectrum, as Schuster shows, superposed on that from the nucleus, when the temperature gradient became sufficiently steep. This type of spectrum would hold until the star cooled down below the point at which the vapour of the carbon present congealed into droplets of solid carbon, forming a cloud-layer or photosphere in the star's atmosphere.

When this critical temperature was reached, the star's spectrum would evidently undergo a profound change. The cloud layer, if deep enough to be opaque, would entirely cut off the bright-banded spectrum coming from the nucleus, and in its place give us an absolutely continuous one,

* Wilson and FitzGerald, 'Roy. Soc. Proc,' vol. 60. We were engaged in measuring, by means of a Boys' radio-micrometer, the radiation coming from the positive carbon in an electric arc-light while surrounded with different gases under high pressure.

The arc was enclosed in a strong iron box, on one side of which was attached a steel tube which was closed at its furthest end by a strong lens of quartz. This lens formed an image of the arc on the radio-micrometer.

We found that by suddenly reducing the pressure of the gas in the box, there were convection currents set up in the steel tube, which were able to scatter the light coming from the arc so that the carbon suddenly seemed to become only red hot, and even in some instances the incandescent carbon became quite invisible for some seconds. But for the fact that the ammeter showed us that the current was flowing steadily, we would have assumed that the arc had been quenched.

FitzGerald immediately made the suggestion that we had here an explanation of the cause of the darkness of sun-spots.

Also Schuster ('Astro-physical Journal,' 1905) shows mathematically that this result would be produced by molecular scattering of light, or scattering by suspended particles.

on which would be superposed the dark-line Fraunhofer spectrum as we see in the sun.

In a sun-spot we get a glimpse of the solar spectrum like what it was while the sun was so hot as to prevent the condensation of the carbon clouds. Dr. Johnstone Stoney* was the first to point out this view of the nature of the solar photosphere. He suggested that in the true surface of the photosphere we have a region where the carbon clouds are absolutely raining. The droplets of solid carbon thus fall to a lower level, where the temperature is high enough to re-vaporise them again. A sun-spot seems to be due to an up-rush of hot gases with a temperature high enough to vaporise the clouds, so that we are able to see down into the gaseous nucleus below. The penumbra of a sun-spot may be a region where the carbon rain has ceased and where the clouds are of the nature of cirrus or fog.

The ordinary Fraunhofer spectrum would then be due only to the vapours of such elements as from their atomic weight would lie above the carbon clouds, in addition to such vapours as get carried up by the powerful convection currents which must exist on account of the rapid temperature gradients caused by the great radiation from the clouds. The spectrum of a sun-spot is just what we should expect if the radiation is coming from a gaseous layer hotter than the clouds; for it consists of bright bands and lines, crossed by the absorption lines of the vapours which lie between the cloud layer and the deep-seated part of the inner gaseous nucleus.

When we increase the depth or the partial pressure of a vapour giving an absorption spectrum we get more and more dark lines, and also a widening of them into bands, until ultimately when the depth is sufficient to become opaque, the spectrum, as has been previously shown, must assume the character of a continuous one.

Sir William Huggins has shown that by reducing the partial pressure of calcium vapour, the numerous lines in the spectrum of this body gradually disappear, leaving H and K only. And Liveing and Dewar record an observation showing that it is even possible to wipe out the K line, when the remaining spectrum consists of only the one line H.

If, instead, the absorption spectrum of calcium vapour were observed, the first lines to appear would thus be H and K; then as the partial pressure was increased they would be followed by the other lines.

I think we may here have an explanation of that striking phenomenon which is sometimes seen when observing sun-spots, namely, that some of the lines are distorted, showing rapid motion in the line of sight, while other lines of the same element are not affected at all.

* 'Roy. Soc. Proc.,' vol. 16, 1868.

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In the case of calcium just cited, let us suppose that in the sun we are looking through a vast depth of say, 50,000 miles of calcium vapour: if a storm were blowing on the upper surface, but only extending to say a depth of 1000 miles, the H and K lines would be distorted, but the other lines in the spectrum which are only produced by the deeper layers would not be affected at all.

If we take a tube containing a transparent gas such as hydrogen, and observe with a spectroscope the light passing through it from a source giving a continuous spectrum, we can see no dark absorption lines due to the gas as in the solar spectrum. And probably we would have to increase the depth of gas to many miles before we would see the lines. In the sun we are able to look through from 10,000 to 100,000 miles of hydrogen, and from the sharpness of the lines in the solar spectrum we have strong evidence that even that great depth of gas is still almost quite transparent. Thus we are led to the possibility that if the sun were expanded into a nebula, say 10 times the diameter of Neptune's orbit, it would give the bright line spectrum still.

Other substances such as sodium become opaque when the thickness of their vapour is comparatively small; this shows how minute on this view the partial pressure of sodium vapour and other vapours like it must be in the solar atmosphere.

It seems thus tenable that the sun's atmosphere consists principally of hydrogen and helium with only minute traces of such substances as sodium.

In the great nebula in Orion it is permissible to suppose that the depth is about equal to the breadth. Its immeasurable distance from us shows us what a stupendous depth of gas lies between us and the stars beyond, and yet their light shows no falling off in brilliancy. This indicates with what extraordinary freedom ordinary light is able to pass through untold millions of miles of hydrogen and helium. It thus seems not improbable, as above urged, that if all the hydrogen at present in the solar system were again expanded into a nebula, say with a diameter of 10 times the orbit of Neptune, it would then, if seen from a distant star, still give a bright line spectrum the same as Orion now gives to us. The volume of a nebula of this size would be of the order of 10^{15} times that of the sun; if the sun were expanded to this size the partial pressures of such substances as sodium, which now in the sun are so small, would become evanescent, and their spectra would probably be quite invisible, so that we can conceive that the solar nebula in its early stages of evolution gave a spectrum quite similar to many others now visible in the heavens. It would thus appear that hydrogen and possibly helium are the principal constituents of the atmospheres of all stars and nebulae, and that most of the other elements are present in much smaller

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quantities; and that the spectrum of a star may depend far more on the partial pressures of these elements in the star's atmosphere than on its temperature.

Great caution is needed in regard to assuming that, because certain stars have a spectrum of lines which are only seen in the spark, they must be at a higher temperature than other stars that do not show these lines. We seem to have little direct evidence that would justify us in stating that the spark is hotter than the arc. The conclusion that it is so seems to have been formed mainly because in the spark spectrum we often get more lines, and these are generally more towards the violet. It seems quite conceivable that the abrupt and oscillatory discharge in the spark is able to excite vibrations in the atoms irrespective of the temperature of the gas. At any rate it would be difficult to produce direct experimental evidence showing that in the spark we have a high temperature in the strict sense. In the arc we undoubtedly have a high temperature; but even there, may not atomic disturbances be set up by the electric current, such as would give rise to certain lines in the spectrum which would not be visible if the gas could be heated say in an oven to the same temperature?

Some very interesting experiments bearing on this have been lately recorded by A. S. King.* He repeats some earlier experiments made by Liveing and Dewar, and his work leads him to the following conclusion: "This shift of maximum in the spark towards longer waves, in connection with the behaviour of the caesium series at different temperatures, would point, on its face, to the conclusion that the arc is of a higher temperature than the spark, in contradiction to the view generally held; though our knowledge will not enable us to deny that most of the spark properties usually deduced as evidence of higher temperature,† such as great brightness with small volume, richness of spark spectra in ultra-violet lines, etc., may be the result of the more violent electrical action.‡ However, the modern view points to something so different from a thermal radiation in the spark, that it seems as if the word 'temperature' cannot be used in the same sense for both arc and spark."

If we take a Plücker vacuum-tube containing a trace of air, the most feeble *electrical* discharge through it will make the gas glow brilliantly and give a

* "On the emission spectra of metals as given by an electric oven," 'Astro-physical Journal,' April, 1905.

† Liveing and Dewar, 'Roy. Soc. Proc.,' vol. 44, pp. 241 and 242, 1888.

‡ J. Hartman and G. Eberhard, "On the Occurrence of Spark Lines in Arc Spectra," 'Astro-physical Journal,' No. 3, p. 229, 1903; J. Hartman, "On a new Relationship between Arc and Spark Spectra," 'Astro-physical Journal,' No. 4, p. 270, 1903; H. Crew and J. C. Barker, "On the Thermal Development of the Spark Spectrum of Carbon," 'Astro-physical Journal,' No. 2, p. 61, 1902.

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bright line spectrum ; even rubbing the outside of the tube with a cloth will make it glow. But if we send a beam of light from a glowing solid body through the tube when thus excited, we do not see the absorption spectrum of air. Even the depth of our atmosphere is not sufficient to bring out all its absorption lines, as we see an enormous increase in their number when the sun is near the horizon. This appears to be evidence that the electrical discharge is able to make the air give an emission spectrum quite irrespective of its temperature. If it were a temperature effect we ought to get some trace of an absorption spectrum by looking through the tube at a continuous source of light.

If we could *heat* a column of air, of the same depth as our atmosphere, to a temperature sufficiently high to make it radiate waves up to its extreme ultra-violet lines, we would then on the present view get a bright-line spectrum identical with the absorption spectrum we get when the sun is in the zenith ; and if we could heat to the *same temperature* a column of air of the depth that a beam of light traverses when the sun is on the horizon, we would get an enormous increase in the number of bright lines, in the same position and density as the dark lines we observe in the absorption spectrum with a low sun.

If we could reduce gradually the depth of our column of air keeping the temperature the same, we should get less and less bright lines, in the same way as we would get less absorption lines, and ultimately when the depth of the column was sufficiently reduced we would be unable to get either bright lines or dark ones.

As has been pointed out earlier in this paper, substances vary enormously in the density or partial pressure that they require to give an emission or absorption spectrum. A few inches of sodium vapour will give a far darker absorption spectrum than we get in the sun, indicating that the partial pressure of that substance in the solar atmosphere must be of extreme tenuity.

Magnesium vapour is probably very opaque. Some years ago (1895), I was engaged in measuring the thermal radiation from sun-spots with a Boys' radio-micrometer, using a large image of the sun about 3 feet in diameter, which was thrown on a screen in the laboratory by a heliostat. There was a fairly large spot on the disc, and my eye at once detected a brilliant green patch on the side of the umbra and partially covering it. It was shining like a green lamp. I then observed it with the solar spectroscope, and found all the magnesium lines brilliantly reversed. I also took a photograph of it with the photo-heliograph.

The area of this magnesium cloud was probably about 60,000,000 square

miles. It has always seemed very difficult to explain the origin of a cloud like this mainly of one substance only, like magnesium; but if we assume that the partial pressure of magnesium in the solar atmosphere is almost evanescent, the smallest increase of its density would greatly increase the intensity and number of its lines. The reversal of its spectrum merely showed that the vapour was at a much higher temperature in the spot than in the neighbouring photosphere.

If the vapours of the different elements in the sun lie below the photosphere more or less in layers according to their atomic weight, while the reversing layer above the photosphere is made up of a mixture of a great number of them by convection currents, is it not conceivable that some vapours like magnesium get carried up from below and temporarily increase their partial pressure locally in the atmosphere? The quantity of vapour thus required to bring out more enhanced lines in the spectrum would possibly be quite minute.

To summarise this paper; it seems that—

1. If the temperature of a star is sufficiently high to enable the gases, if dense enough, to emit all their lines up to the extreme ultra-violet, then an increase of temperature would have very little effect in altering their spectrum.
 2. Differences in the partial pressure of any one gas in two stars of the *same temperature* may have a very large effect in determining the lines that would be seen in its spectrum.
 3. Stars whose temperatures were slightly above and below the critical point at which the photospheric clouds are formed would differ largely in their spectrum.
 4. From the above causes it would seem impossible to classify stars on a scale of temperature alone.
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